Economic modeling of the CO_2 transportation phase and its application to the Duero Basin, Spain

Bernardo Llamas, Álvaro Hernández, and Luis Felipe Mazadiego, Technical University of Madrid, Spain
Juan Pous, Technical University of Madrid and VALORIZA, Madrid, Spain

Abstract: Carbon capture and storage is a viable option to reduce greenhouse gas emissions. Although capture and geological storage of CO_2 are the major forms of research, CO_2 transportation should be also considered in the entire chain. There are still some issues that require a more accurate definition, especially in economic aspects. In this study, we explore concepts such as the uses of a storage structure for a single source with, for instance, an individual transportation line, and the use of a centralized model using a geological structure for several co_2 emitters. This model has been applied in a given region of Spain, in order to determine the maximum distance between the sources and the potential areas for storing CO_2, using a geographical information system to evaluate the data. Moreover, sensitive analysis was performed in order to provide a better understanding of the economical implications of CO_2 transportation

Introduction

Continuous increases in greenhouse gas (GHG) emissions[1] have been related to global warming. In addition, the European Commission has recently presented an ambitious strategy to reduce GHG by 2030,[1–4] and is leading a new worldwide agreement to control and reduce anthropogenic GHG.

Global warming is a complex issue in which countries should cooperate in multilateral agreements. However the reduced use of fossil fuels as primary energy is the main point of disagreement. Developing countries favor the continued use of these sources, as this is the cheapest way to obtain energy, whereas developed countries consider renewable energy as the next generation and most sustainable source of energy in the future. However, the International Energy Outlooks estimate that fossil fuels will continue as primary energy sources up to year 2035 and beyond.[5,6] Given such a scenario, carbon capture and storage (CCS) has been highlighted as one of the most promising technologies to significantly reduce CO_2 emissions from industrial activities, including steel and cement plants, power stations, and other related enterprises.[7,8]

The Intergovernmental Panel on Climate Change (IPCC) estimates that the worldwide potential to store CO_2 equates to decades of GHG emissions.[8] In recent years, much research has been carried out to scale-up different technologies to capture CO_2 from stationary sources. Nonetheless, financial feasibility has not always been achieved. Furthermore, the social implications of long-term storage of CO_2 need to be taken into consideration.[7] In relation to this, one key

Table 1. Current CO_2 pipelines. The first long-distance CO_2 pipeline was in the 1970s. Main utilization of the natural & anthropogenic CO_2 is EOR activities.[10,13]

PIPELINE	Location	Length Km	Diameter inches	Estimated Maximum 10^6t/year
Cortez	USA	808	30	23,6
Sheep Mountain	USA	656	NA	11,0
Bravo	USA	351	20	7,0
Dakota Gasification/Weyburn	USA/Canada	328	14	2,6
Choctaw	USA	294	20	7,0
Bairoil	USA	258	NA	23,0
Central Basin	USA	230	16	4,3
Canyon Reef Carriers	USA	224	16	4,3
Comanche Creek	USA	193	6	1,3
Centerline	USA	182	16	4,3
Delta	USA	174	24	11,4
Snohvit	Norway	153	NA	0,7
Borger	USA	138	4	1,0
Coffeyville	USA	112	8	1,6
OCAP	The Netherlands	97	NA	0,4
Beaver Creek	USA	85	NA	NA
Anton Irish	USA	64	8	1,6
El Mar	USA	56	6	1,3
Chaparral	USA	37	6	1,3
Doliarhide	USA	37	8	1,6
Lacq	France	27	NA	0,1
Adair	USA	24	4	1,0
Cordona Lake	USA	11	6	1,3

element of importance is the transportation (infrastructure to transport CO_2 which is captured from any stationary source to a suitable and safe sink) criteria associated with the existing European CCS projects and their impact on project feasibility.

This paper evaluates the economic implications of CO_2 transportation by pipeline, considering different scenarios, namely Point to Point (P2P-CO_2) versus a centralized network (CN-CO_2) transportation as a strategy to implement this technology across Europe. This study defines a short distance (less than 200 km) to avoid any pressurized station[9,10] and considers different quantities of CO_2 to determine the cost of each assumption. In order to determine the feasibility of each assumption, the authors define hypotheses (breakdown economy of the CCS chain) and different scenarios for the cost of CO_2 allowances.

A case study is proposed in Spain, which considers current stationary sources that are located in a sedimentary basin. In this case, appropriate structures for storage of CO_2 close to those sources are expected to be found.[11,12] Using a Geographic Information System (GIS) and the financial analysis proposed in this paper, it is possible to compare point-to-point scenarios with a centralized network. The results are analyzed from a technical and financial perspective.

Materials and methods

Current CO_2 transportation

The relative development of technologies to capture and store CO_2 is still in its early stages. This is reflected by the low number of existing infrastructure developed to transport CO_2 from stationary sources into geological structures. Table 1 provides an overview of the current developments for CO_2 transportation globally. All of these examples have been developed as a result of to the enhanced oil recovery (EOR) technique,[13] where the CO_2 source is found mainly in natural reserves. In Europe, only a few projects are in operation, but there are plans to deploy an extended CO_2 pipeline network along Europe in order to optimize CO_2 storage structures.[14]

These examples may be used to study CO_2 conditions. In addition, many CO_2 pipeline projects are based on well-known designs and materials commonly used in natural gas pipeline specifications. The most profitable way to transport CO_2 is in its dense phase.[15,16] However, topographic variations during transportation of CO_2 in the liquid phase could induce pressure differences, turning liquid into gas. This can generate a two-phase flow, which has many associated handling difficulties.[15,17] Therefore, it has been suggested that the most efficient way to transport CO_2 is as its supercritical phase, which occurs at a pressure higher than 7.38 MPa and a temperature of more than 31.1 °C.[15,18] In order to maintain these conditions, this type of transportation may require the use of booster stations in the pipeline layout so that the required pressure and temperature are maintained.

It has been suggested that the operating pressure of CO_2 pipelines should be above 10.3 MPa,[9] which ensures that CO_2 will always be in a single phase over a range of temperatures. This range of temperatures is generally defined by the temperature of the surrounding soil. For example, in northern latitudes, the soil temperature varies from a few degrees below freezing in winter to 6–8°C in summer, while in tropical locations the soil temperature may reach up to 20°C.[15] One more design constraint is the construction material of the pipeline. An in-depth analysis of the allowable operating conditions for several materials has already been provided in the existing literature.[19]

However, there is no need for a temperature limit. In the pipeline diameter calculations, the ambient temperature of the pipeline is assumed in most cases and CO_2 is compressed to transport it as a supercritical or liquid phase.[8,9] It must be taken into consideration that pipelines are often buried[16] mainly for environmental safety purposes, but this also provides more stable temperatures than at the surface, where pipelines can reach high temperatures as a result of sun exposure.[21]

Materials and pipeline specifications

Material selection should be compatible with all states of the CO_2 stream. These materials should be selected to prevent corrosion and allow maximum material stress. In addition, eligible materials need to withstand the potential low temperature conditions that may occur during a pipeline depressurization situation.

The design of a pipeline should meet the requirements set by appropriate regulations and standards. CO_2 pipelines shall be designed according to the applicable regulatory requirements. The Recommended Practice for Design and Operation of CO_2 refers to the following pipeline standards: ISO 13623:2009, DNV-OS F101:2012 and ASME B31.4 or ASME B31.8.[22] Pipeline material specification can be defined according to the requirements of the American Petroleum Institute (API) 5L (or other standard) with additional clauses in order to ensure that the material will be suitable for the specific purpose.[23] The pipeline material may be chosen on the basis of cost analysis, where potential pressures for transferring CO_2, pipeline diameter and thickness are also determined.

Usually CO_2 pipelines are designed using existing national standards for gas and liquid transportation pipes, while additional CO_2 specific design issues are taken into consideration by the pipeline construction/operation companies to guarantee the reliable and safe operation of a given pipeline.

As previously stated, the requirements for CO_2 pipelines are expected to be incorporated into existing pipeline standards in the near future. Several standards and recommended practices are applicable to CO_2 pipelines. For example, the ISO 13623 is a general international standard, although most countries operate under their own primary pipeline standard.[24]

Carbon-manganese steels are the cheapest suitable pipeline material for CO_2 transportation, and are used wherever possible.[25] This combination is generally coupled with corrosion inhibition technologies, since it offers inadequate resistance to internal corrosion by the transported fluids thus requiring the use of corrosion resistant materials. Pipelines designed for transportation with high risk of corrosion may be, therefore, manufactured in solid corrosion-resistant alloy (CRA), in carbon steel cladding, lined with CRA, or made as flexible pipes.[23]

The use of carbon steels (e.g. with API X-60 and X-65) for the transportation of CO_2 streams has been ongoing for more than 30 years as required in EOR

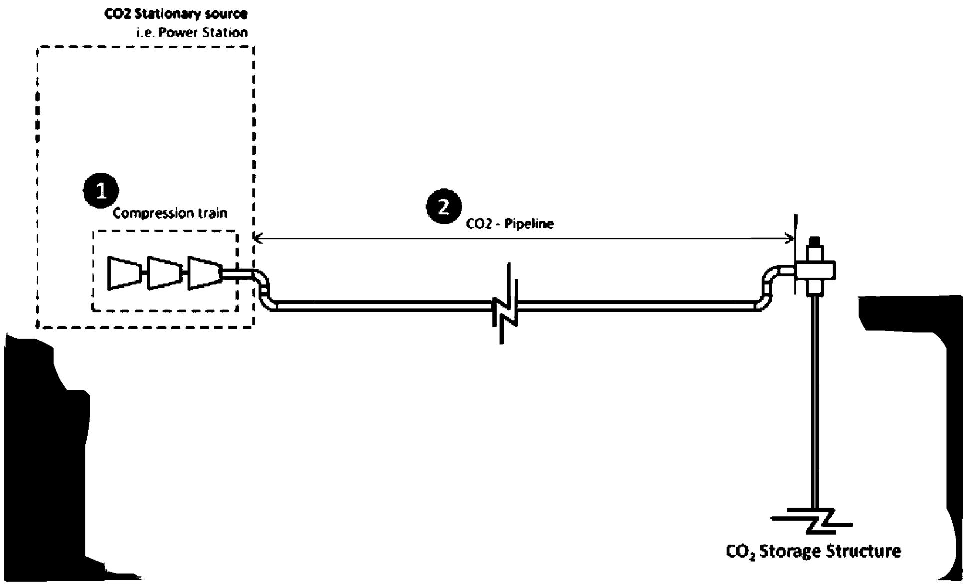


Figure 1. Schematic representation of the main units considered in the costs analysis of CO_2 transportation in the present study.

projects. Field experience confirms that corrosion rate is low. It has been reported that a carbon steel pipeline system operated with high-pressure CO_2 over 12 years will endure a corrosion rate of only 0.25-2.5 μm per year.[8] This is mainly a result of the high focus on controlling the water content in the CO_2 before it enters the pipeline, and the strict procedures for shutting down the line in case the dewatering system cannot meet the specifications. For CO_2 service at high pressures in valves, control seals and packing special CO_2 resistant materials like nylon or viton are considered appropriate.[20] During the 2002–2008 period, 18 incidents were reported with no fatalities and/or injuries.[26]

CO_2 transportation design

The cost of transporting the CO_2 to the site must be added to the cost of storing the CO_2 at the location.[9,27–29] Moreover, the cost of pipeline transportation will be determined by the pipeline route, in which physical and social geography will be crucial conditions.[30] Finally, the lithology of the area will play an important role, as well as the characteristics of the pipeline itself, such as the length, diameter, material, quantities, and sharpness of bends and number of booster stations (if applicable).

Considering the amount of CO_2 that needs to be transported and the required distances, on-shore pipeline routes are thought to be the most economical.[15,19,21] The scenarios considered in this paper are based on the cost estimate carried out by the Global CCS Institute.[10]

The three major cost elements for pipelines are (i) construction costs (e.g. materials, labor, booster station, if needed, and others), (ii) operation and maintenance costs (e.g. monitorization, maintenance, energy costs, etc.), and (iii) other costs (design, insurance, fees, and right-of-way).[31] Special consideration should be given to certain land conditions, like heavily populated areas, protected areas such as national parks, or major waterways, which may have significant cost impacts.[8,32]

The approach proposed in this study includes the cost of the infrastructure needed to transport CO_2 downstream to the Capture Unit (Fig. 1). Therefore, a compression train and the distance between source and storage structure are considered in the cost estimate. This study proposes a limited distance of 100–200 km to avoid any re-pressurization stations.[9,10]

Calculation

The Duero Basin as an area to evaluate different transportation and cost scenarios

An improved understanding of the proximity of major CO_2 sources to suitable storage sites, coupled with the establishment of cost curves for the capture, transportation, and storage of CO_2, would facilitate decision-making about large-scale deployment of

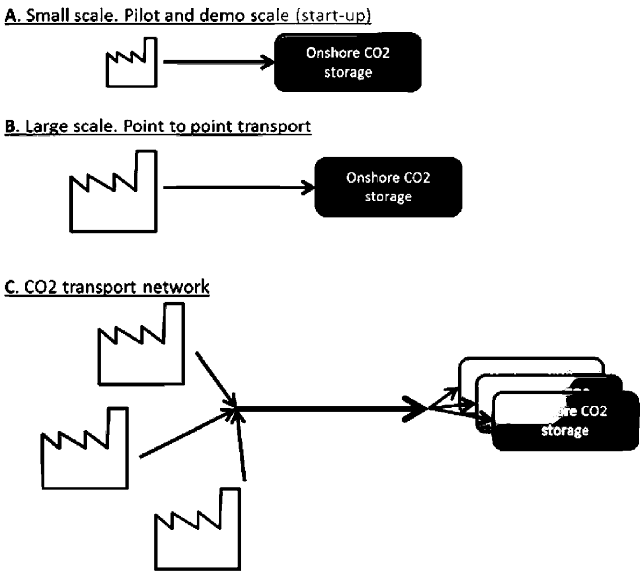


Figure 2. Three scenarios are considered in this case-study.

CCS[8]. For this reason, it is necessary to evaluate both storage options and CO_2 emission sources.

The Duero Basin in NW Spain is one the most promising basins for CO_2 storage in the Iberian Peninsula due to the existence of favorable deep aquifers close to large CO_2 emission point sources.[29] The geology of this area suggests different structures and formations that might be suitable as a CO_2 storage structure.[11,12,30]

There are several stationary CO_2 sources along the Duero Basin. Most of these are power stations in which the main primary energy is autochthonous coal. This provides an interesting scenario for assessing different strategies for CO_2 transportation. The power stations considered in this area reflect 25% of the total capacity installed in Spain, which uses coal as primary energy. It is therefore likely that the results obtained in this study could be extrapolated to rest of Spain. For the purpose of this study, the power stations of Compostilla II (León), La Robla (León), and Velilla/Guardo (Palencia) have been selected. In addition, Anllares (León) will be also considered in the integrated network scenario. Table 2 includes current CO_2 emissions from these sources and the capacity of each of them.

This study considers three scenarios in order to evaluate (i) point to point transport (Scenarios A and B) and (ii) integrated network (Scenario C). Scenario A has also been included to compare the cost between the *deployment phase* and the *mature phase* of this technology.

This geographical area has been subject to previous studies that have proposed many structures as suitable areas for storing CO_2, such as the ALGECO2 Project (led by the Spanish Geological Survey) and the GEOCAPACITY Project (FP7 Project, supported by the European Commission). This area might be suitable from several perspectives: various suitable structures have been identified, and the presence of the Utrillas formation – located in this area – provides the optimal criteria to store and contain CO_2.[30]

A specific GIS has been developed in order to evaluate the different routes and the most cost-effective way to transport CO_2. Final definition of the CO_2 transportation route will be defined in the detailed engineering, but some aspects were taken into account in this study in order to produce a consistent investigation: Routing pipelines through urban areas or across waterways can increase transportation costs, while using existing pipeline infrastructure and rights of ways can reduce these costs. It is convenient to avoid existing infrastructure, and densely populated areas (e.g. cities, towns).[13]

CO_2GeoRef application as a source to evaluate pipeline designs

Once the project concept, the capacity, and some other basic parameters have been set, most of the detailed work on route selection will be addressed in subsequent project phases. However, GIS could be used to store, process, analyze, manage, and display all types of geographical data. This research has been developed using the GvSIG® software. It is an *open-source* software. Source code is easily accessible, so it can be modified, extended, and distributed for non-commercial purposes.[33] GvSIG® has also been reported as easy to install, user friendly, efficient, capable, providing wider accessibility to data in different formats, and powerful.[34]

Several basic principles must be taken into account because there are some differences on route selection between CO_2 pipelines and other gas pipeline which can lead to errors.[13]

The first condition of this study is to avoid the intermediate compression station, which limits the maximum distance to transport CO_2. Circles shown in the figures represent two radios: 100 and 200 km. Potential storage areas identified in the ALGECO2 project have been plotted as dark brown areas in order to evaluate the distance between sources and storage

Table 2. CO_2 emissions from selected stationary sources in the Duero Basin, Spain.[31,32] Differences between 2009 and 2012 emissions are due to political reasons (subsidies).

	Energy source	Capacity (MW)	CO_2 emissions (10^6·t/y) 2012	CO_2 emissions (10^6·t/y) 2009
CT. Velilla/Guardo	Coal	516	1,70	0,93
CT La Robla	Coal	655	2,23	0,74
UPT Compostilla II	Coal	1.171	5,05	2,64
CT Anllares	Coal	365	1,59	0,28

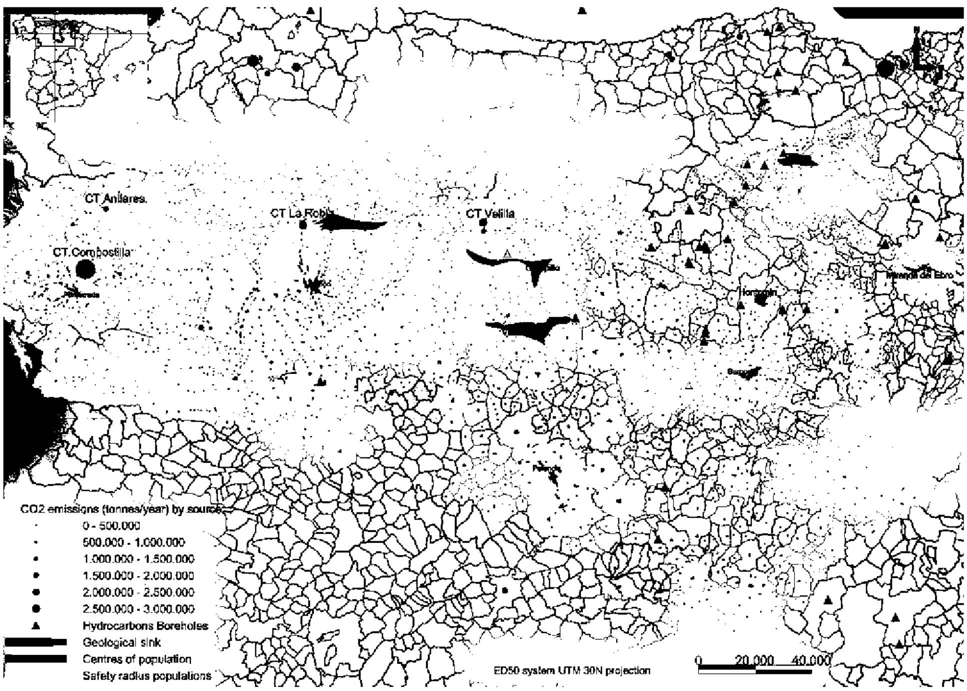


Figure 3. Towns and their areas of influence that should be avoided.

Table 3. Interactions proposed in this study (Source-Sink).

		Boñar	Campillo	Villameriel
1	CT. Veilla/Guardo		A, B	B
2	CT La Robla	A, B		
	(1) +(2)		**C**	**C**
3	UPT Compostilla II		A, B	A, B
4	CT Anllares			
	(3)+(4)		**C**	**C**
	(1)+(2)+(3)+(4)			**C**

(A) small scale, P2P model; (B) large scale, P2P model; (C) integrated network)

areas. Lack of data on these geological structures, all of which have been identified as deep saline aquifers, is the main hurdle when properly defining these structures. The areas were defined by previous hydrocarbon explorations, which included well drilling and seismic data acquisition. Hydrocarbon exploration wells are indicated by orange triangles in Fig. 3. Only the Boñar structure was defined without being based on a well and few seismic data were recorded in this area. For this reason, the authors considered this

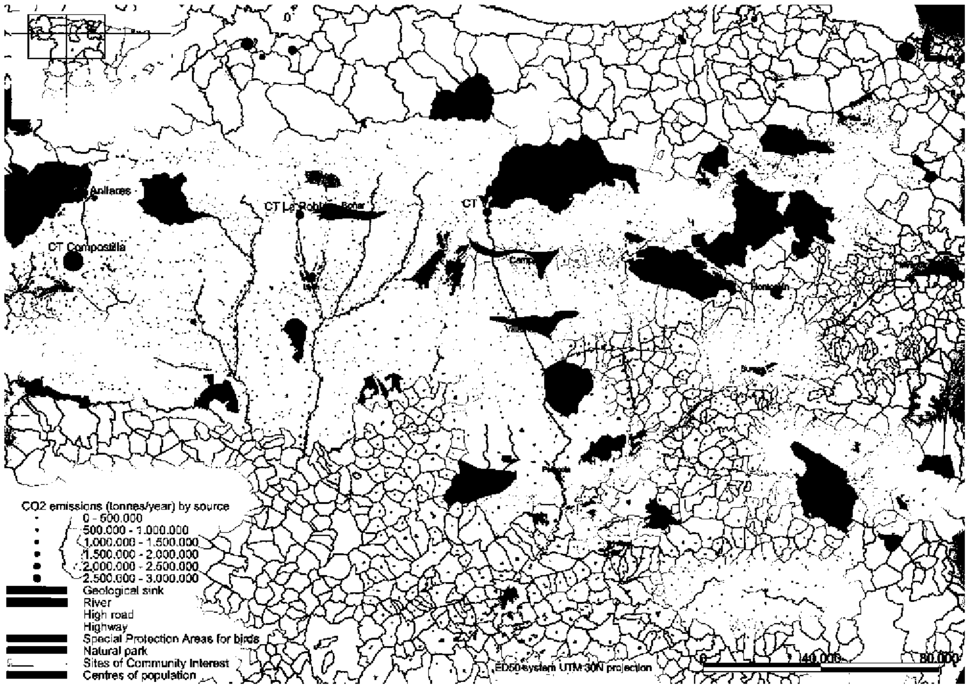


Figure 4. Environmental and ecology areas are considered in this study. Those areas should be avoided in the preliminary pipeline design. Main infrastructures and watercourses are also included.

structure less promising, leading to its removal from the C model (integrated network). Table 3 summarizes the interactions proposed in this study between source and sink.

Secondly, interference or proximity to potential or current infrastructures must be minimized by avoiding human habitats where possible. For this reason, a safety radius has been proposed for different towns, depending on the number of inhabitants: Populations of more than 1000 inhabitants have been allocated a safety radius of 5 km and populations of more than 5000 inhabitants have been given a safety radius of 10 km. Both radii are represented by yellow areas (Fig. 3).

Ecologically sensitive or environmental areas must be also avoided. For this reason, different protected areas have been considered (Fig. 4), namely Special Protection Areas for Birds (SPAB), Sites of Community Interest (SCI), and Natural Parks (NP).[35,36] In addition, difficult watercourse (superficial stream of water, river, or brook) and highway crossings should be avoided where possible.

Choosing a terrain that is relatively easy for pipeline construction should also be considered. In our case, the area of this study corresponds to a sedimentary basin (Duero Basin), where main formations are clays, sandstones and limestone, which are suitable for an easy pipeline construction. Finally, a digital elevation model (DEM) has been included, because it is necessary to evaluate the slopes of the pipeline route. Both data will complement and evaluate the terrain surface (Fig. 5). Using the DEM, a longitudinal profile can be produced to identify the best route without major elevation changes, preventing pressure drops in the pipes and therefore higher costs of installation of new compression equipment.

Other geo-referenced parameters have not been considered due to lack of data (e.g. future developments that might be incompatible with the presence of CO_2-pipelines).

Cost calculation

Any cost assessment which is not based on price contract is an estimate. Even if the deviation of the cost assessment has an accuracy of ±30%, the cost estimated in literature[37–39] must be consistently assessed, and will give an order of magnitude of the investment required for the CO_2 transportation phase. The cost calculation should include several technical characteristics in order to determine the diameter,

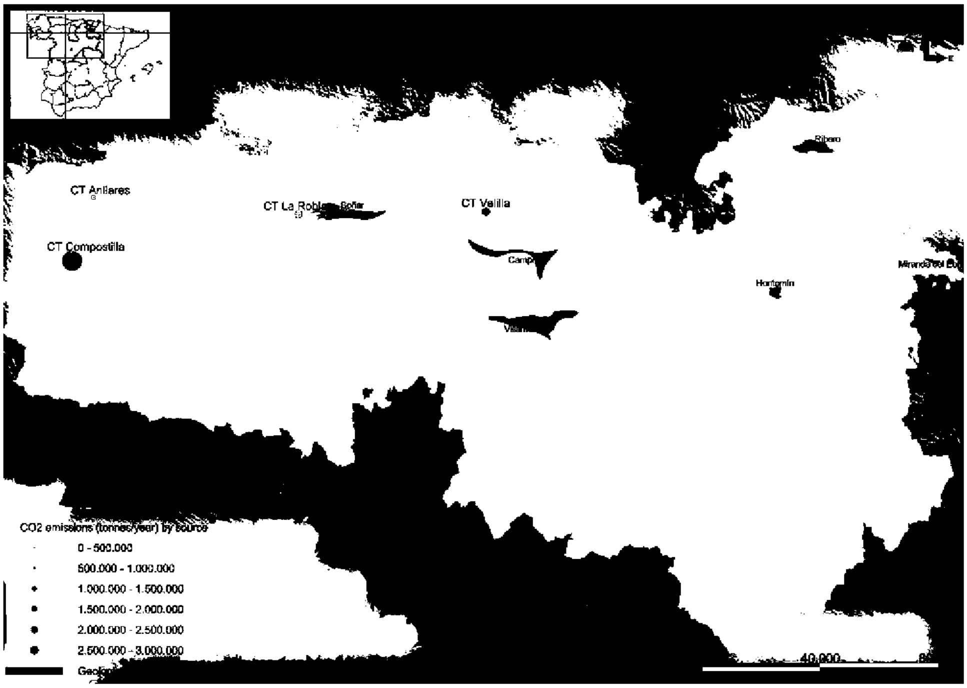


Figure 5. Digital elevation model (DEM) and geology.

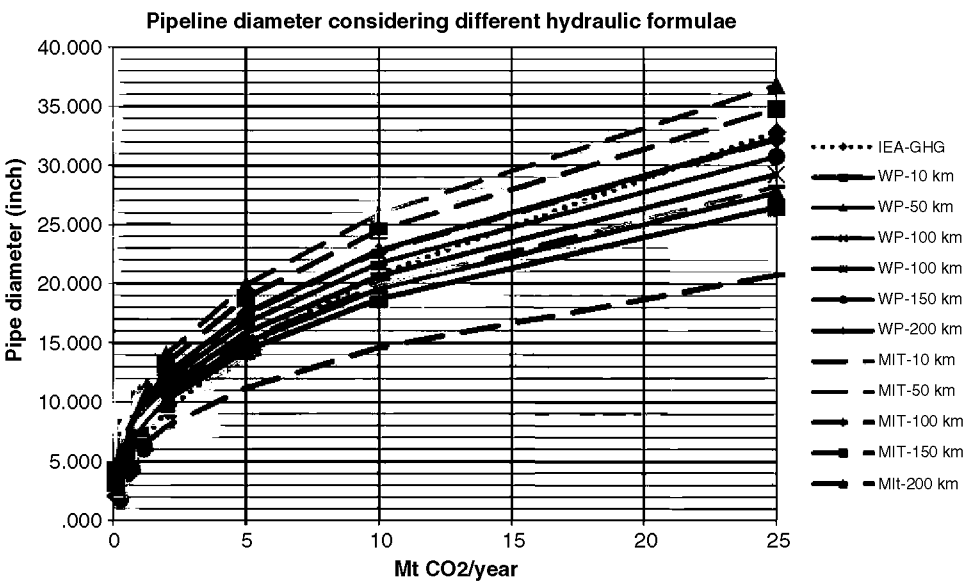


Figure 6. Pipeline diameter calculation using different formulae. Calculations are made considering different pipeline capacity.[10,38,39]

thickness, length of the pipelines as well as the allowed pressure drop for a given mass flow-rate of CO_2.[37,38] In this study, technical characteristics for each design have been assumed to be the same. The only difference between each scenario is the distance and the capacity of each stationary source. For instance, pipeline section is calculated on the basis of several hydraulic equations: Massachusetts Institute of Technology (MIT), Carnegie Institute of Technology, Worley Parsons, and the Carbon Capture and Storage Institute (Fig. 6).[10,38,39]

The capacity of the pipeline is the first design criterion required for a CO_2 transportation cost estimate. Pipeline capacity will be fixed by the pipe

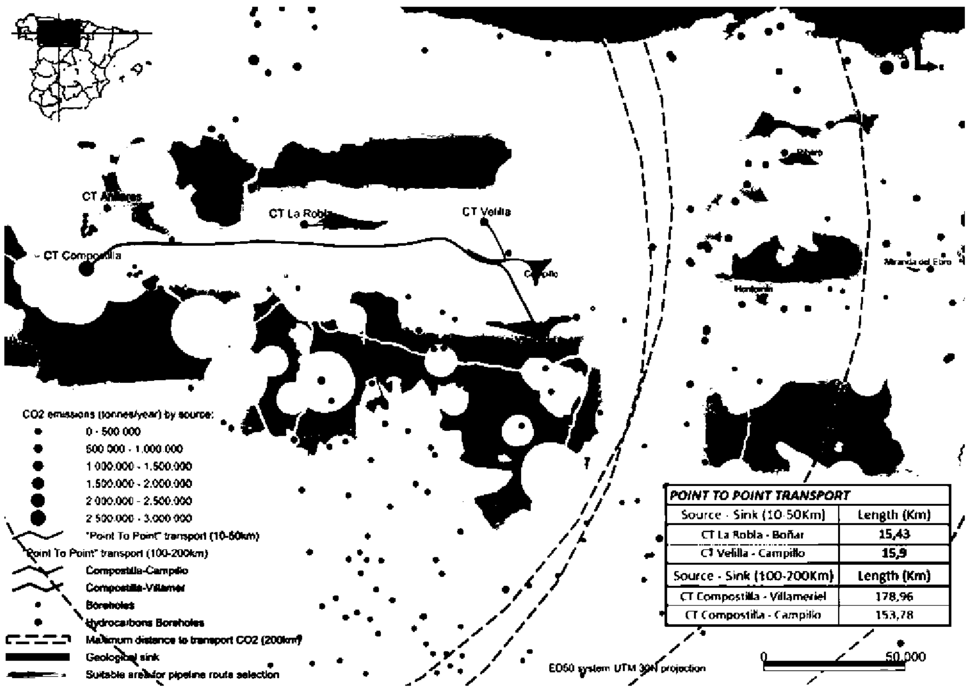


Figure 7. General overview of the pipeline traces. P2P model.

section and the operating pressure, and pipelines need to be appropriately sized for the given CO_2 source.

A calculation model has been created to determine the pipe diameter, taking into consideration the length of the different scenarios (Table 3). The diameters obtained for each method are rather similar,[38,39] so it may be possible to determine the diameter for each scenario that is being considered in this study according to the standard pipe diameters (API5L).

Figure 6 represents the pipeline diameter for each volume of CO_2 transported per year. It shows that an IEA-GHG formula (provided by CCS Institute) is one of the formulae that provides the average value to all the formulas considered.

Results

The main factors considered for selection of an optimal route include public safety, environmental impacts, land uses, terrain definition (geotechnical conditions), and proximity to existing relevant infrastructures and facilities (i.e., highways, watercourses, and industries).

The methodology applied is based on the definition of the specific GIS, which integrates the geospatial information. The CO_2 emitters and CO_2 storage structures information define the beginning and end of the route. The pathway of the CO_2-pipeline will be defined thanks to the integration of the geospatial information which is mentioned in the previous paragraph.

Considering these conditions, several routes have been proposed (Table 3), in order to evaluate the technical-economic feasibility of each route. Prior models were based on P2P designs (Fig. 7), but a number of other routes have been considered using in the integrated network model (Figs 8 and 9).

Pipeline designs indicate that the source-sink distance is relatively low, considering La Robla and Velilla sources. In this case, both sources have been evaluated considering the nearest sink, and the distance in these cases is less than 16 km. In contrast, Compostilla source does not have any sink in the near proximity, so the distance calculated is of greater magnitude: 179 km if the sink is the Villameriel storage or 154 km if the potential CO_2 storage is the Campillo area. Nevertheless, both distances are less than 200 km, and no intermediate booster station has been considered in the economic analysis. The P2P scenarios have been evaluated considering an early stage (pilot scale) and industrial scenario. Pilot scale considers a total capacity of 100 kilo-tones of CO_2.

In order to evaluate the most suitable scenario, the method provided by the CCS Institute has been used, which considers the cost (both CAPEX and OPEX) of

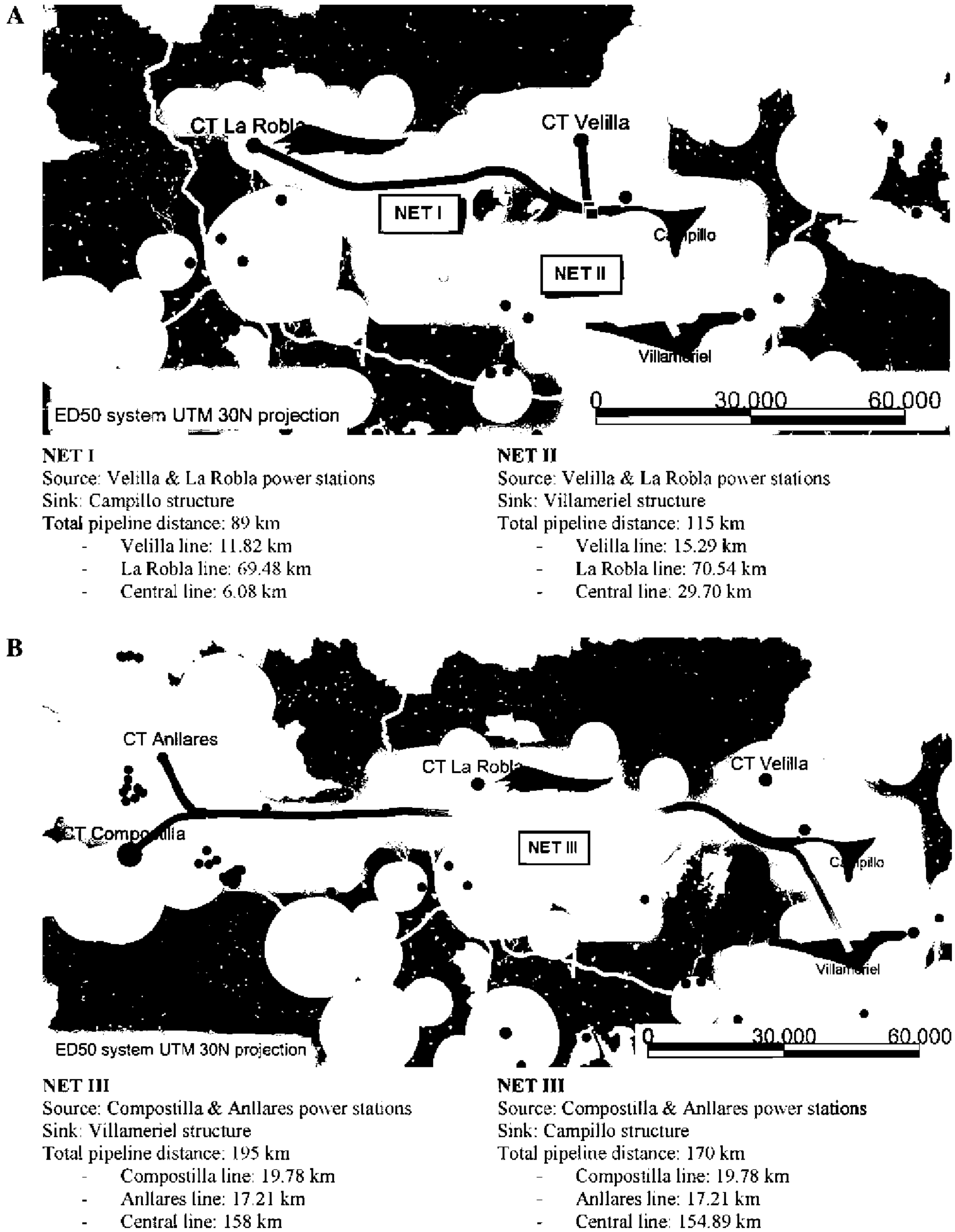


Figure 8. General overview of the pipeline traces: (a) La Robla & Velilla sources and Campillo & Villameriel as a sinks (NET-I and NET-II). (b) Compostilla & Anllares sources and Villameriel sink (NET-III).

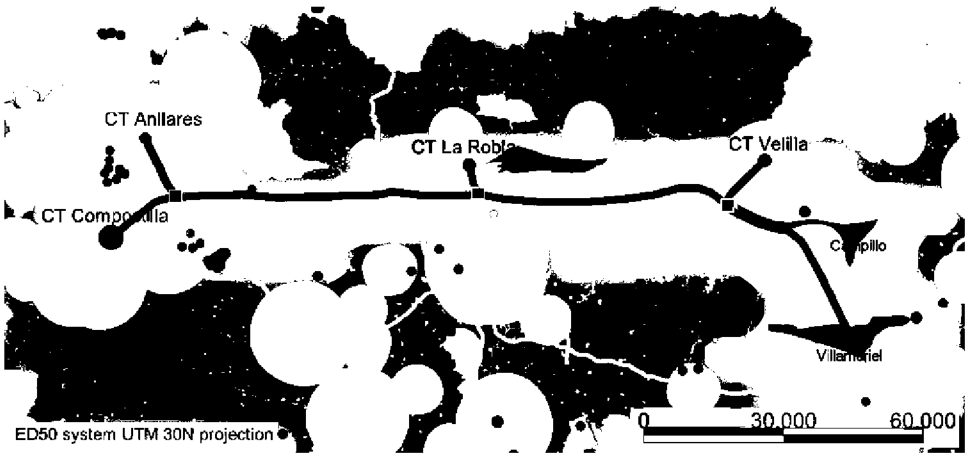
the transportation system. Pipeline cost in Fig. 10 includes a booster station in the stationary source, CAPEX and OPEX of the pipeline the latter (OPEX cost also considering the cost of electricity consumption). Equation (1) shows the costs of CO_2 transport (InvPipe), consider the CCS Institute formulae.[10]

$$\mathrm{InvPipe} = (C1 \times L + C2 + (C3 \times L - C4) \times D) + ((C5 \times L - C6) \times D2) \times 10^6 \times TF \quad (1)$$

where Terrain Factor (TF) has been considered as an average value and the rest of constants are based on onshore values published by the CCS Institute (Table 4).

The length for each design and section is included in Figs 7 and 8, and 9, whereas the pipeline diameter is calculated based on hydraulic formulae published by the same organization.[10]

Different industrial scenarios have been evaluated considering the entire volume of emissions of the



TOTAL NETWORK
Source: Compostilla, Anllares, La Robla & Velilla power stations
Sink: Villameriel structure
Total pipeline distance: 213 km

- Compostilla line: 17.36 km
- Anllares line: 14.96 km
- La Robla line: 7.14 km
- Velilla line: 12.89 km
- Central line: 161.09 km

Figure 9. General overview of the total network considered for all the sources considered in this study.

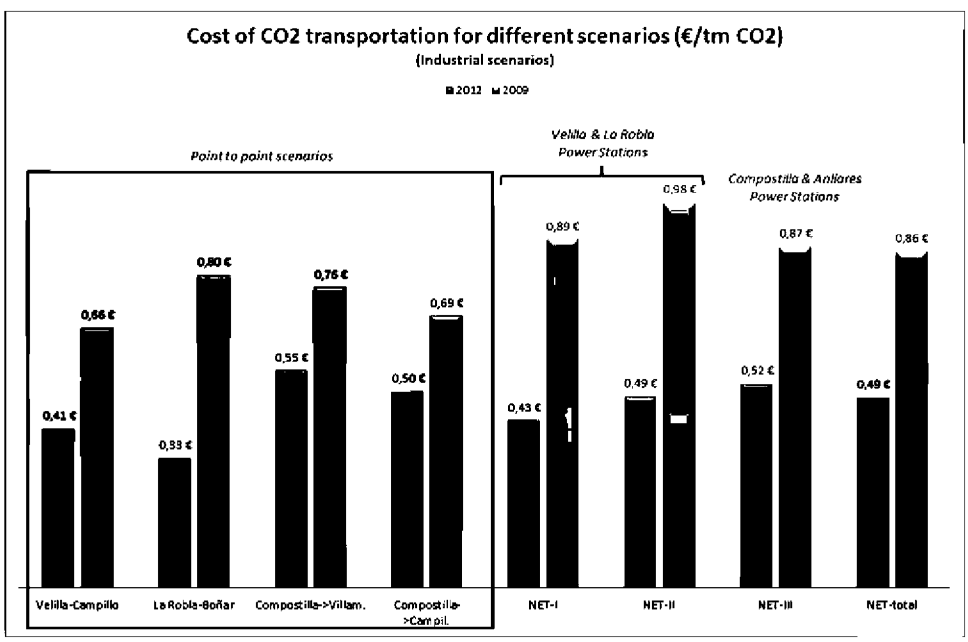


Figure 10. Cost of CO_2 transportation for different models, considering low (2009) and normal (2012) emissions.

stationary sources over a period of 20 years, in which normal (2012 year) and low (2009 year) emission data have been considered. The pipeline section is assessed considering both scenarios (Table 5).

It is assumed that the normal emissions scenario is the most suitable data for evaluating the results. Nevertheless, a low emission scenario is considered in case of incidental low energy demand or the

Table 4. Values of the variables considered in Eqn (1).[10]

	C1	C2	C3	C4	C5	C6	TF
Values (On Shore conditions)	0.057	1.8663	0.00129	0	0.000486	0.000007	1.20

Table 5. Pipeline diameter considering different scenarios.

	Pipeline section (inches)	
	Normal emissions scenario	Low emissions scenario
CT. Veilla/Guardo	8.58	6.34
CT La Robla	9.82	5.67
UPT Compostilla II	14.78	10.69
CT Anllares	8.29	3.45

establishment of a policy for higher use of renewal energy.

Results showed in Fig. 10 indicate that the CN model is less expensive in comparison with a decentralized model:

- For a decentralized network or point-to-point scenario, the cost would be 1.24 €/t CO_2. And in this case, the Anllares power plant has not been included to avoid an extra cost.
- In the intermediate scenario, considering two networks – NET-I which includes Velilla and La Robla Power Plant whereas NET-III includes Compostilla and Anllares Power Plant – the cost associated with this scenario is 0.95 €/t CO_2, considering the Campillo structure as a storage site.
- When the cost is associated with an overall network where an integration of the whole pipeline designs is 0.49 €/t CO_2, the Villameriel structure is the storage site.

Conclusions

Transportation of CO_2 onshore is a common practice in countries such as the USA or Canada, where there are several EOR applications in oil fields. Nevertheless, few CO_2 transportation applications are related to the geological storage of CO_2. According to the IEA, it will be necessary to build as many as 500 000 km of CO_2 pipeline by 2050. For this reason, it is still necessary to consider the most efficient model to transport huge quantities of CO_2 from stationary sources to suitable geological structures.

Results shown in this paper are based on the CO_2GeoRef tool, which consider several criteria in the pipeline design. CO2GeoRef is an iterative model which integrates geospatial information in order to define the pre-feasibility design of CO_2 pipelines; it is based on geospatial and non-geospatial information. This software tool allows an easy evaluation and assessment of any alternative to be performed. In this case, the data are based on the Duero Basin, where there are larger emitters and different storage areas.

Two different models (point-to-point or network models) have been considered, in order to evaluate the cost of three scenarios – small-scale, point-to-point and network models – at an industrial scale. The centralized network is almost 60% less expensive in comparison to the point-to-point model. It shows that a consensus will be needed regarding the design of future routes to transportation CO_2 in an efficient way.

According to EU Directive 2009/31/CE, it is necessary to guarantee access to transport networks by third parties (art. 31);[47] for instance, the network model will also require a coordinated design of the pathways in which an independent institution should guarantee all health, safety, and environmental aspects, to enhance the social acceptance of this mode of transportation. One single institution should be responsible for requesting the rights of access and transportation.

CO_2 transportation costs depend mainly on the distance and the quantity of CO_2 to be transported. Two different scenarios were evaluated in this paper (normal emissions – conventional operation of the power plants – and low CO_2 emissions). The difference between normal and low emissions can increase the cost between 73% and 75% considering point-to-point and total network models.

Future power plant locations should consider the CCS chain; for this reason, it will be necessary to evaluate the distance between the stationary source (emitter) and the CO_2 storage area in order to render any CCS project financially viable. Even if the cost associated to transport is less than 10% of the total CCS chain,[8,46] it is necessary to optimize the route to decrease its cost, and social and environmental issues.

Although the results presented in this paper are based on a specific area of Spain, the CO_2Georef GIS and Excel® sheet used in the evaluation of each scenario may be used at a regional or national level. For instance, the tools developed are compatible with any other region or country, and can be used as a preliminary design for the future CO_2 pipeline transportation network in large areas (i.e., European Community or North America regions).

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Bernardo Llamas

PhD and Mining Engineer. Professor at the Technical University of Madrid in the field of project management and subsurface exploration. Expert on different scientific fields, with four international patents and several articles in the field of CO_2 storage, Biomethane and microalgae.

Álvaro Hernández

Mining Engineer and Master in Project Management. Actually working in the business development area of OHL Industrial, which performs full Engineering, Procurement and Construction for Industrial Power Plants as international contractor, focused on thermal and renewable power generation.

Luis Felipe Mazadiego

Ph.D. in Mining engineering and UPM Professor at the Madrid School of Mines. Secretary of the Oil & Gas Engineering Master degree (UPM). He has participated in projects on oil exploration geochemistry, characterization of hydrocarbon contaminated soil, environment and shale and geological storage of CO_2.

Juan Pous

He was Director of Innovation at multinational infrastructures and services company Sacyr for 10 years. A Doctor in Mining Engineering and Associate Lecturer at UPM since 1996, he has been principal investigator on many R&D projects, including improving energy efficiency, and developing models for CO_2 storage in deep geological formations.